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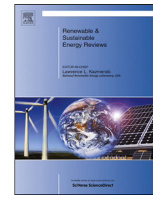

Life Cycle Analysis (LCA) of photovoltaic panels: A review

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A B S T R A C T

The environmental impact of photovoltaic panels (PVs) is an extensively studied topic, generally assessed using the Life Cycle Analysis (LCA) methodology. Due to this large amount of papers, a review seems necessary to have a clear view of the work already done and what is still to be done.

The objective of this paper is to present an accurate overview of the LCA already performed on PVs. The analyses are classified by panel type and by impact assessment methodology. When available the information relative to the PV system (efficiency, localization, etc.) is also summarized.

The following main observations are noted:

- Silicon panels are the mostly studied, thin layers on a lesser extent, while new panel types, such as organic, are not yet considered.
- Regarding the study scope, Balance Of System (BOS) components, although influential, are often omitted and their characteristics (efficiency, etc.) are sometimes not provided. This is the same for the End of life.
- Most studies focus on energy related indicators such as the Energy Payback Time (EPBT) and indicators relative to climate change such as CO_2 emissions. When impact assessment methodologies are used, it is generally Eco-Indicator99 and sometimes CML. But, results are, unfortunately, sometimes expressed only after normalization

Finally, this review underlines the necessity to achieve further LCA on photovoltaic panels, as many aspects are still in need of evaluation, such as the electronic properties of the panel or BOS components.

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1. Introduction

The use of photovoltaic panels (PVs) for electricity production has rapidly increased in recent years, even though their environmental impacts are still not fully determined. A lot of work has recently been undertaken in this respect, generally with the use of the Life Cycle Analysis (LCA) methodology. A wide variety of results is obtained, mainly due to the importance of the PV system (module type, efficiency, etc.) and the way the methodology is applied (functional unit, boundary, etc.). A summary of the main results of these studies is presented in this paper.

Reviews on LCA of PVs have already been published [1–3]. However, they are about specific panel type or specific environmental indicators. Peng et al. (2013) [3] investigated only energy consumption, Energy Payback Time (EPBT) and global warming potential (GWP). The study of Sumper et al. (2011) [1] is focused on emissions of CO_2/kW h and EPBT, and Sherwani et al. (2010) [2] only consider silicon-based panels. The aim of this paper is to provide an up-to-date review on LCA of PVs of all the panel types, describing the panels and underlining the methodology used.

The first section provides a brief definition of the LCA methodology. The second part concerns the review where results are divided by PV types to allow comparison among studies. Some studies compare different PV types and are cited separately. The last part focuses on the "Balance of the System" (BOS) components. These are all the components of a PV system other than the panel itself.

2. The LCA methodology

The LCA methodology evaluates and quantifies the environmental impacts for every stage of a product's life. The ISO 14040 and 14044 standards [4,5] provide general guidances to perform a LCA. There are four interdependent stages: (1) goal and scope definition, (2) Life Cycle Inventory (LCI), (3) impacts assessment, and (4) results interpretation. During the first stage the functional unit and the system boundary are determined. In the second stage, the full life cycle is decomposed into elementary steps and for each step the energy and material balances are performed. All the environmental impacts are evaluated in the third stage: for each flow from the LCI, a specific characterization factor determines its impact in the studied impact category. A specific score is finally obtained for each impact category studied. Normalization can also be used. In this case, the results are expressed in relation to a reference, such as the mean impact of an European citizen. This can help in determining the categories that have the most impact, although normalization should be used with caution.

In this review, results of previous works are summarized. Assumptions relative to the LCA, as e.g. functional unit, system boundaries or impact methodology are also examined.

3. LCA of PV systems

The first LCA publications on PVs appeared in the mid-1970s [6,7], but are now outdated considering the achieved improvements of PV technology. This review focuses on studies published after 1990.

3.1. Silicon PVs

Crystalline silicon modules are the most extensively studied PV type since they are the most largely used. The studies summarized here are divided between conventional, i.e. environmental LCA, and nonconventional LCA (social LCA, cost LCA, etc.). The main results of the conventional LCA of silicon PVs are presented in Table 1. This table also presents the mains hypotheses taken into account for the LCA analysis.

3.1.1. Conventional LCA

The indicators about energy balance, such as the Energy Payback Time (EPBT) are extensively used in LCA of energy production devices. Greenhouse gas (GHG) emission is also a widely used indicator. Other studies use more exhaustive impact assessment methodologies such as CML [8] or Eco-Indicator99 [9]. To illustrate this point, the studies are classified regarding the indicators used for the impact assessment.

3.1.1.1. Energy and emissions. Pacca et al. [10] compared polycrystalline silicon PVs (efficiency of 13%) with amorphous silicon (efficiency of 6.3%) in an installation of 33 kW h on the roof of the University of Michigan. The Net Energy Ratio (NER), the EPBT, and the CO_2 emissions are calculated. The NER of polycrystalline modules is 2.7 and the EPBT reaches 7.4 year versus a ratio of 5.14 and 3.15 years for amorphous silicon. For the CO_2 emissions, the latter obtains 34.3 g CO_2-eq/kW h versus 72.4 for the former. Sensitivity analyses are also performed about panel efficiency and energy saving during fabrication. Moreover, the advantages of using photovoltaic electricity during panel production are underscored.

Stoppato [11] has examined polycrystalline silicon PVs (efficiency of 16%), with results calculated for several countries by taking into account their irradiation and their electric mix. In Belgium, the EBPT is 6.241 year and the avoided CO_2 emissions are 0.1954 tCO_2-eq/kWp.

LCA of a 200 kWp polycrystalline silicon PVs installed in Spain is performed [1], taking into account steps from raw material extraction to electricity generation. The functional unit is the production of 1 kW h electricity. The EPBT is between 3.5 and 5 years, depending on the irradiation. Most of the energy consumption can be linked to module production step. A comparison with other PV types shows that thin layer PVs have the smallest energy consumption and that monocrystalline silicon PVs produce lower emissions than the studied panel. The ecological footprint method is also applied to the system.

PVs with tracking systems have also been studied by Perpiñan et al. [12]. They make a review and then add their own data. Modules are in silicon with an efficiency of 12.4%. Systems connected to the grid are studied and the environmental advantages of using tracking systems are demonstrated: the EPBT of the studied system is always under 5 years.

Facade-integrated PVs have been examined. In their study, Perez et al. [13] studied a Façade integrated PV system with waste-steam mono-Si installed in New-York. The functional unit is the production of 1 kW h. The BOS components are included and the performances are measured in situ. Two scenarios are considered: in the first one, the wafers, coming from waste stream have no environmental impact; in the second one the wafers are produced specifically for the studied system and are included in the LCI. The EPBT in the first scenario is less than 1 year and in the second is 3.8 years. The GWP calculated by the IPCC GWP100a methodology is respectively 10.2 and 60.5 g CO_2/kW h.

Sometimes, PVs are compared with other renewable electricity production systems as it is the case in 2005 with the comparison

Table 1
Summary of the mains results about silicon PV.

Study	Panel type	PV system	Country	Modules efficiency	FU	Boundaries	Methodology	Mains results
[1]	Poly.	Roof-mounted	Spain		1 kW h	Production (BOS), installation and use	EPBT	EPBT 3.5–5 years
[10]	Poly. and amorphous	Roof-mounted	US	From 6.3 to 13%	1 kW h	Production (BOS) and use	EPBT CO_2	EPBT: 3.15–7.4 year CO_2: 34.2–72.4 g/kW h
[11]	Poly.	Roof-mounted	Severals locations (EU, Austria, US)	16%	0.65 m^2 panel	Production and use	EPBT CO_2	EPBT 3,5–7 year CO_2: 50–800 g/kW h
[12]	Crystalline	Tracking system	South Europe and North Africa	12.4%	1 kWp	Production (BOS) and use	EPBT	EPBT <5 year
[13]	Mono.	Facade-integrated	US		1 kW h	Production (BOS) and use	EPBT IPCC (GWP)	EPBT=3.8 year GWP=10.2 g/kWh
[14]	Poly. and mono.	Roof and façade	Switzerland	From 13.2 to 14.8%	3 kWp	Production (BOS) and use	Eco-Indicator 99 EPBT	EPBT=3–6 year GWP=136–100 g/kW h
[15]	Poly.	Ground-mounted	Italy	14.4%	1 kWp	Production (BOS) to EoL	Eco-Indicator 99	CO_2 (with Eco-Indicator):8.74 g/kW h
[16]	Poly.	Tracking system	Spain	13.1%	1 kW h	Production (BOS) to EoL	IPCC 2007 (GWP) EPBT Eco-Indicator 99	EPBT=1.45–1.5 years
[17]	Mono.	Building Integrated Concentrated	Spain			Production	Eco-Indicator 99 (Norm) EPS 2000 (Norm)	
[18]	Poly.	Roof-mounted	Netherlands		1 kW h	Production (BOS) to EoL	Eco-Indicator 99 (Norm)	
[19]	Poly.	Ground-mounted	Germany	12.5%	1 kW h	Production (BOS) and use	Eco-Indicator 99	GWP=0.063 kg/kW h
[20]	Mono.	Tracking system	Italy	13.8%	1 MW h	Production and use	Eco-Indicator 99	EPBT= 5.5 years GWP=44.7 g/kW h.
[23]	Poly. and mono.	Roof-mounted	South-European locations	From 11.5 to 14%	1 kWp	Production and use	CML 2000	EPBT: 1.7–2.7 year CO_2: 30–45 g/kW h
[24]	Crystalline			15%	1 kW h	Production	EPBT CO_2 CML 2000 (Norm)	Direct CO2 emissions $<<$ indirect
[25]	Amorphous/ nanocrystalline	Roof-integrated	Netherlands	10%	1 kW h	Production (BOS) and use	ReCiPe EPBT	EPBT=2.3 year

FU= Functional Unit. Boundaries: (BOS): the BOS components are included in the LCA – EoL: End of Life. Methodology: (Norm): the results are only expressed after normalization – CO_2==CO_2 emissions calculation.

of a PV with a wind turbine [14]. Thirteen PVs are considered, ten of which are designed for small scale installations. Mono and polycrystalline silicon modules are taken into account, their average efficiencies being 14.8 and 13.2%, respectively. Eco-Indicator 99 is used and the EPBT is determined. Depending on PV type and localization, the GHG emissions are between 39 and 100 g CO_2-eq/kW h and the EPBT between 3 and 6 years for the annual mean irradiation in Switzerland (1100 kW h/m^2/year).

3.1.1.2. Impact assessment. In this section, papers using an impact assessment methodology are described (classified by methodology). The most common methodology is Eco-Indicator99. ReCiPe, which is the most up-to-date methodology, is not yet largely used.

3.1.1.2.1. Eco-Indicator99. The first study using Eco-Indicator is about a PV plant [15]—a ground-mounted installation of 1777.48 kWp built with 14.4% efficiency modules in Italy. The boundaries start at ground preparation and finish at the end-of-life (EoL: recycling) including maintenance (replacement of some BOS components, etc.). Eco-Indicator99 is used to assess environmental impacts. The module production has the most significant part in most of the impact categories except for ozone layer and minerals depletion where electric connections exceed. With normalization, the greatest damage is caused by use of fossil fuels and exploitation of mineral resources ("Resources" category), but impacts on human health are also important, especially relating to respiratory inorganics and climate change. Finally, the advantages of PVs compared to coal, natural gas or petroleum are underscored.

The entire life cycle, including EoL, of tracking PV systems is also studied [16]. The polycrystalline silicon PV's modules used have an efficiency of 13.1%. The functional unit is chosen as the production of 1 kW h of electricity. With a tracking system, a PV receives 30% of additional irradiation. The system localization has a heavy influence. For example, the CO_2 PayBack Time (CO_2PBT) varies between 3.49 and 4.6 years for the same tracking PV system installed in different Spanish areas. The tracking system itself and PV type are also influent. The Eco-Indicator99 methodology is also used and underlines that the module production is the most damaging step.

Concentrated PV systems is studied by Menoufi et al. [17]. They study a Building Integrated Concentrated PV (BICPV) system installed in Spain and compare the results with a theoretical Building Integrated PV (BIPV) system. They use Eco-Indicator99 and EPS 2000 methodologies. The BOS components such as the installation and transportation are not included. The results underline that the CPV system represents only more or less 10% of the environmental impact when the other 90% are due to the building. The BIPV scheme used instead of the BICPV causes an increment of about 10 to 13.5% of the environmental impact. With Eco-indicator99, the total impact score is mostly dominated by three impact categories: fossil fuels, respiratory inorganics, and climate change. In the EPS 2000, the three most dominant impact categories are: depletion of reserves, life expectancy and severe morbidity. A sensitivity analysis underlines that the higher the concentration factors, the lower the impact scores.

A comparison between a polycrystalline silicon PV module and a wind turbine was performed in 2011 using Eco-Indicator99 with normalization [18]. BOS components and EoL are taken into account, contrary to most studies. Two possibilities are studied for the PV EoL: burying the waste in landfills or recycling them. During the PVs production, the most damaging step is the module production. The highest impact categories, in decreasing order, are

fossil fuels depletion, respiratory inorganics effects and minerals depletion. When both EoL scenarios are compared, an important reduction of the environmental impact in all categories, except for fossil fuel depletion, is obtained with recycling (especially for the respiratory inorganics effects and carcinogen effects). When compared with wind power for the production of 1 kW h of electricity, PVs have higher environmental impacts, except for ecotoxicity, land use and minerals depletion when wind turbines are not recycled. Wind power produces a quarter of the fossil fuel depletion and half of the respiratory inorganics effects of PVs.

Another study [19] compares polycrystalline silicon PVs (efficiency of 12.5%) with an anaerobic digestion plant working with maize. When looking at GHG emissions, acidification or eutrophication with Eco-Indicator99 methodology, the PVs obtain higher environmental benefits. When co-generation is performed at the anaerobic digestion plant, its environmental performances improve but remain lower than those obtain by PVs. Nevertheless, biogas production is not intermittent and manure or organic wastes digestion can perform better since they do not require a dedicated crop.

Finally, a study compares monocrystalline silicon PVs (efficiency of 13.8%) ground-mounted with a single-axis tracking system with thermodynamic cycles [20]. The two installations are located in Italy. The BOS are not included because there are very similar for the two plants. The Eco-Indicator99 is used. For PVs, the greatest environmental impact is related to modules production. When normalization is used, the use of fossil fuel and the respiratory inorganics effects give the main contribution to environmental impact. When compared with thermodynamic cycles, the PV scenario obtains higher environmental impact excepted for the following categories: carcinogens, ecotoxicity, land use and minerals. Both installations are compared with more accuracy on CO_2 emissions and EPBT. In both cases, the thermodynamic cycles perform better. Nevertheless, the EPBT for the PVs is 5.5 years, which is smaller than its life expectancy.

3.1.1.2.2. CML. Thanks to the CrystalClear project founded by the European Union and dedicated to the LCA of silicon PVs, an extensive inventory is available [21]. Eleven industrial plants of mono (efficiency: 14%) or polycrystalline (efficiency: 13.2%) silicon or polycrystalline silicon ribbon (efficiency: 11.5%) located in Europe have been studied. Recommendations for performing LCA of photovoltaic panel published in 2005 by Fthenakis et al. [22] have been applied. This LCI [21] has been used one year later in a LCA performed with the CML2000 methodology [23]. The functional unit is 1 kWp of modules or 1 kW h when comparisons with other electricity sources are made. The main highlight of this study is that ribbon modules perform best followed by polycrystalline modules.

The GHG emissions during polycrystalline silicon modules (efficiency of 15%) production have been calculated by Reich et al. [24]. They consider only the panel production. The emissions are divided into direct (from raw materials) and indirect (from energy consumption) emissions. The latter are clearly more important and are dominated by electric consumption for the production. Different energy sources used for panel production are studied when indirect emissions are investigated. The advantages of using photovoltaic electricity during panel production are underscored in 7 impact categories after normalization (GWP100, ozone layer depletion, human toxicity, photochemical oxidation, acidification, eutrophication and nonrenewable energy). They probably use the CML methodology but it is not stated explicitly in the paper. An impact reduction of at least 25% is obtained compared to the case where the average European electricity grid mix is used. Finally, horizon 2050 is examined: the greater the number of installed PVs, the smaller the GHG emissions.

3.1.1.2.3. ReCiPe. Recently, Mohr et al. [25] have investigated the environmental impact of a PV using the ReCiPe methodology at both Midpoint and Endpoint levels. The PV is composed of amorphous silicon/nanocrystalline silicon (a-Si/nc-Si) with an efficiency of 10%. It has a service life of 20 years and it is installed in The Netherlands. The BOS components are included (coming from Ecoinvent database) but not the EoL due to the lack of data. They are compared with multi-Si PVs with an efficiency of 14.4% and a service life of 30 years. The functional unit is the production of 1 kW h. For all environmental impact categories, the multi-Si panel gave the best performance except for photochemical oxidant formation and terrestrial ecotoxicity. When normalization is applied at Endpoint level, for the both PV types, the categories damage to human health due to climate change, human toxicity and particulate matter formation together account for more than 60% of the overall score. The EPBT is also determined: 2.3 years for a-Si/n-Si PVs and 3.4 for multi-Si PVs. The contribution of each life cycle step of a-Si/n-Si PVs to the Primary Energy Demand and to Climate Change is also determined. Some sensitivity analyses are performed on energy demand.

Table 1 summarizes the main results of the studies described below. This allows to underline that, for all the study where it is calculated, the EPBT for the PVs is always smaller than its life time. So, in regards to energy consumption, the PVs seem environmental friendly. The GWP, when calculated, is always smaller than 150 g CO_2-eq/kW h. It is also interesting to have a look at the different hypothesis made during the LCA. Examination of the results underlines the importance of systems boundaries definition and of panel localization. The studies are generally about panel installed in sunlight area. In regards to systems boundary, only few studies take into account the End of Life of the PVs and the BOS component are not always included. Most of the studies determine the EPBT. Nevertheless, the methodology used is not always well defined. More, the methodologies used for the LCA are most of time Eco-Indicator99 or sometime CML but unfortunately, in some studies the results are only presented after normalization. Only one study used the ReCiPe methodology.

3.1.2. Non-conventional LCA

Some nonconventional LCA are performed on silicon PVs. For example, a hybrid LCA of polycrystalline silicon PVs with an efficiency of 13.2% was performed [26] in 2010. The goal of this methodology is to reduce the error due to lack of data by using an economic approach to complete the LCI. The obtained results are 60% higher than those obtained with a conventional LCA for energy consumption, EPBT and CO_2PBT. Sensitivity analyses are performed on localization.

Another study [27] estimates the cost related to GHG, SO_2, NOx and PM emissions associated to PVs installed in China. The caused damage is used to estimate the damage cost. They find that the co-benefit of using PVs is 0.167 yuan/kW h. They estimate that in 2027 the cost of PVs will reach the same as cost of coal, but if co-benefits are taken into account, the cost can be reached earlier, in 2023. Sensitivity analyses show a heavy influence of the damages cost.

A meta-analysis on LCA about GHG emissions for silicon PVs was performed in 2012 [28]. Only 13 studies meet the whole criteria (original results, consistency with the application, etc.) fixed by the authors. The module efficiency is of 13.2% or 14.0%, depending on module type. The average value for GHG emissions is 57 $gCO_{2\text{-eq}}$ but the harmonized average determined by meta-analysis is 45. The latter is calculated by adjusting the result regarding the different PV properties (efficiency, irradiation, etc.).

Only one study estimates PVs sustainability by performing LCSA [29]. Silicon polycrystalline PVs produced in Germany or in

Italy in 2008 and 2009 are considered. The functional unit is chosen as the production of 1 m^2 of PV since all panels have same properties. In the LCA part, Eco-Indicator99 is used at normalization level. The Italian modules obtained the best performances except for some categories such as ecotoxicity. In the Life Cycle Cost (LCC), the German modules produced in 2009 are the best. Social aspects are studied with a workers view (discrimination, children work, etc.) and Italian modules performed better. A tool to represent these results is also described.

3.2. Thin layers PVs

There are very few studies dedicated to thin layers PVs. As there are different types of thin layers PVs, they are here classified accordingly.

The first LCA on these types of PVs was made in 2005 [30] on CdTe modules with an efficiency of 9%. LCI is performed for the First Solar plant in US taking into account steps from raw material extraction to PV installation including the BOS components. The EPBT is 1.2 year and the GHG emissions are 23.6 gCO_2-eq/kW h. This panel type has smaller environmental impact than silicon ones.

A recent study [31] examines, using LCA, a new EoL treatment based on mechanical process and recycling system for thin film PVs. Only the EoL is considered in this study and a CdTe module is considered. The Impact 2002+ methodology is used. The results underline the environmental advantages of this new EoL treatment. It allows environmental benefits in all environmental impact categories except for Ionizing Radiation and Land Occupation. The environmental advantages of the new system are mainly due to the recovery of glass and cadmium telluride (CdTe). The results are also presented after normalization. By comparing with the old process, the environmental advantages of the studied technology are clearly underlined. Indeed, the old technology obtains worst environmental impacts in all the impact categories.

The GaInP/GaAs thin layer panels with an efficiency of 28.5% are also studied [32]. The electricity used for PVs production comes from same PVs installed in Western Europe. Ten impacts categories (CML 2001) are considered and the advantage of using photovoltaic energy during PVs production is underscored in all the categories except for toxicity.

The future of PVs thin layers is studied by LCA [33] taking into account land and materials' availabilities as the environmental impacts, as well as cost. The present efficiency of the module is 13.2% but different scenarios are considered for future PVs.

In a recent study [34], a process allowing the reduction of the consumption of silane during the production two thin-films PV types (a hydrogenated amorphous silicon (a-Si:H) based PV and a tandem a-Si:H with a thin film technology based PV) is especially examined. This new process allows the reduction of waste of silane from 85% to 17%. The functional unit is the use of 1 kg of silane. The IPCC 2007 GWP 100a and the energy consumption are determined. In the case of the a-Si:H PV, the energy consumption is reduced, by using the recycling process, from 1146 MJ without recycling to 409 MJ per kg of silane used. The GWP diminishes from 61.3 to 22 kg $CO_{2\text{-eq}}$.

Concentration systems coupled with thin layers PVs are also studied [35]. Cells are composed of GaInP/GaInAs/Ge with an efficiency of 37% and the system is installed in Phoenix, USA. The LCA includes steps from raw material extraction to EoL (recycling) including maintenance (materials used in scheduled maintenance). EPBT is always smaller than 1 year. The primary energy demand is mostly related to production (88.3%) and the maintenance stage represents 6.7%. In the production step, the energy imbedded in the solvents used for cell production contributes to more than 50%. The GHG emissions are between 22 and 27 gCO_2-eq/kW h. The land transformation is divided between indirect land transformation, related to raw material production, (32 m^2/GWh) and the direct one (266 m^2/GWh). For water usages, the indirect component dominates— 682 L/MWh for indirect water consumption compared to 26 L/MWh for direct use. The impact of a change in life expectancy is also studied.

3.3. Miscellaneous PV types

Some studies are about most common technologies and so make average for different PV types to determine their average environmental impact. The energy balance and the energy is the most widely used criteria to make comparisons, although others impact assessment methodologies have been used.

3.3.1. Energy and emissions

For example, in 2006, environmental impacts of the most standard PVs (roof or facade mounted) is determined for 41 cities in 26 OECD countries [36]. EPBT, Energy Return Factor (ERF) and potential for CO_2 emissions mitigation are used as indicators. In Brussels, 3.2, 8.4 and 5.9 are respectively obtained for rooftop-mounted PVs whereas the values are 4.7, 5.4 and 4 for facade ones. Globally, EBPT is between 4.7 and 1.6 years for rooftop-mounted PVs and between 2.7 and 4.7 for facades. ERF is between 8 and 17.9 (roof) or 5.4 and 10.1 (facades) and CO_2 emissions mitigation can be, when the best case is considered, up to 40 (roof) or 23 (facades) tons of CO_2 per kWp installed.

Four PV types were studied by LCA in 2008 [37]— silicon ribbon, silicon mono or polycrystalline and CdTe thin layer. Silicon module data come from CrystalClear project whereas for CdTe, they come from Fthenakis et al. [30] (efficiency of 9%). GHG, SO_2 and NO_x emissions are determined and, for the first time, heavy metals emissions are studied. Emissions are divided between direct emissions and indirect. Direct emissions are the emissions occurring at the production plant whereas indirect emissions are related to downstream and upstream processes such as energy generation. Indirect heavy metal emissions, resulting from fossil fuel combustion are calculated for each PV types, whereas the direct emissions are only determined for thin layers panels. Nevertheless, the latter are 10 times smaller than the former. Moreover, cadmium emissions occurring when PVs are used to electricity production are smaller than for traditional electric sources. Finally, use of PV electricity during panel production is also studied. Another study [38] about the same PV types obtains same results for GHG, NO_x, SO_x and heavy metals emissions. The efficiencies of the silicon ribbon, silicon poly- or monocrystalline modules are 11.5, 13.2 and 14% respectively and the efficiency of the CdTe module is 9%. Concentration systems are also considered. A risk assessment concludes that the highest risk during PVs life cycle is related to toxic chemical substances used during modules production. Nevertheless, risks associated with PVs are smaller than for other electricity sources. The future expected improvements in PVs sector are also mentioned.

Other studies examine PVs future such as the work of Raugei and Frankl [39] which starts by examining the different PV types for large or small scale installations: crystalline silicon (mono, multi and with efficiency if 14, 13 and 11% respectively) and thin films (CdTe, amorphous silicon and CIS with efficiency f 10, 7 and 10% respectively). Then, future evolutions in terms of costs, market penetration and environmental performance are determined. Three scenarios are considered within LCA. New works are performed, using this study as a basis [40] in view of determining the Energy Yield Ratio on a PV installation and comparing it with an heavy oil power plant.

PVs are also compared with traditional electricity sources [41]. Silicon cells data come from Wild-Scholten and Alsema (2005)

[21] whereas data about thin layer cells (CdTe with an efficiency of 9%) are from Fthenakis et al. [30] and BOS components data come from Mason et al. [42]. Thanks to the used of PVs, the GHG emissions are reduced compared with petrol, coal or natural gas, but are equal when looking at nuclear.

3.3.2. Impact assessment

A study about 16 PV types with different mounting systems, used to update Ecoinvent database was published in 2008 [43]. The average module efficiency is 16%. BOS components largely influence the results. Different PV types are compared using the Eco-Indicator99 method. CdTe thin layer PVs obtain the worst score and CIS the best one. EBPT is between 2.5 and 4.9 years in Switzerland when the different PV types are considered. A potential GHG emission mitigation map is made for Europe.

In the last study about comparison of different PV types connected to the grid [44], six different PVs with different efficiency types are examined (silicon mono or polycrystalline, amorphous silicon, CdTe, CIS or Si thin layer) in low solar irradiation regions. Thin layer modules obtain a Cumulative Energy Demand (CED) smaller than 30,000 MJ/kWp and so perform better than silicon modules. EPBT is always smaller than 5 years. With Eco-Indicator99, CdTe modules obtain the worst single score. A comparison is made with traditional energy sources and the advantage of using PVs is underscored except when the Individualist weighting is used with Eco-Indicator99 since a short term perspective is considered in which fossil fuels combustion has limited impact.

3.4. The BOS components

Some studies focus on the environmental impact of BOS components even if they are often neglected. A detailed study relative to the BOS components of a 3.5 MWp silicon polycrystalline PV system installed in Springerville (USA) is performed by Mason et al. [42] and the results are compared with those of a similar installation based in Serre (Italy). The Springerville installation used polycrystalline module with an efficiency of 12.2%. It has been realised to optimize costs, materials and works. So, primary energy consumption for the building phase of the whole system is between 526 and 542 MJ/m^2—70 % smaller than the Serre one and EPBT is 0.21 year.

BOS components of different PVs (rooftop-mounted on existing or new roof and ground-mounted PVs) with silicon polycrystalline modules (polycrystalline with an efficiency between 13.2 and 16% and ribbon with efficiency between 11.5 and 15%) are compared in the study of Alsema and Wild-Scholten (2006) [23]. GWP and CED are calculated. PVs integrated in roof obtain the lowest impacts.

These studies underline the importance of including BOS components in the scope of the studies.

3.5. Others

Some studies are not LCA strictly speaking but are clearly related. In 2009, a review of LCA studies relative to PVs is performed [2]. Nevertheless, this study is mostly about silicon PVs. In 2013 [3], another review about the same subject has been published. All the PV types are investigated but only energy consumption, EPBT and global warming potential are considered. They conclude that in the current state of the art, the PVs are environmentally-friendly in these impacts categories.

In 2009, the International Energy Agency has edited a report giving advice about the way to perform PV LCA [45], which is heeded by some of the studies included in this review.

Finally, the influence of consumption profiles on PV environmental impacts is analyzed [46]. The studied PV system operates without connection to the grid so the need for storage has to be considered. Not surprisingly, assimilation of the electricity consumption at the energy production profile to reduce storage needs is the most efficient way to reduce the environmental impact.

4. Discussion

Silicon modules are the most extensively studied PV type because they are currently the most largely used. Thin layer PVs are also a well-documented topic. Moreover, the studied panels are generally installed in sunlight areas. In mean, the thin layer PVs in CdTe obtain better performances in term of EPBT and GHG emissions than silicon based one. Only one study uses a more completed methodology to make this comparison (Eco-Indicator99) [44] and in this case, silicon modules perform better. Nevertheless, when the EPBT is calculated, it is always smaller than the life expectancy of the PVs, for all panel types. It means than in view of energy consumption PVs seem environmental friendly.

When PVs are compared with traditional electricity sources, their environmental advantages are underscored for the impact categories that are mostly considered (Energy consumption, GWP, etc.). This is not always the case if PVs are compared with other renewable electric sources such as wind turbines.

Some parameters that can greatly affect the results of PV LCA are also underlined thanks to this review:

- The electronic performances, such as the efficiency of the PVs, connection type, working voltage, or panel degradation have a high influence on the panel performance and therefore on the results. The efficiency is generally provided in the examined papers but it is not always the case for the others parameters making results comparison difficult.
- BOS components are integrated only in the most recent studies, but their impacts seem non negligible. Moreover, their performance has also a high influence on the results. There are general expressed by a performance ratio but it is unfortunately not included in all the studies. When included, it is generally between 75 and 80%.
- The EoL of the PVs is generally not included due to the lack of data in this field. Nevertheless, it can have a non-negligible influence on the results [18].
- Studies are principally performed for high irradiation areas. Nevertheless, the irradiation is also a critical parameter [47].
- When looking at the used indicators, GHG emissions are generally considered such as energy consumption. But, the latter is not always expressed in the same way (CED, EPBT, fossil fuel depletion, etc.). Eco-Indicator99 is also commonly used and sometimes CML. Unfortunately, the results are sometimes provided only after normalization. When several impact categories are used (like with Eco-Indicator99), the results can be different than by using only energy consumption or GWP related indicators [20].

5. Conclusions

Even if there is a high number of papers dealing with LCA of PVs, this review shows some shortcomings in the topic due to incomplete studies and lack of published details about the system and the methodology. Therefore many results strongly differ and comparisons are difficult.

As a general guideline, the performance of the studied system, along with the BOS components, should be accurately described, and the EoL should be integrated in the study and well defined in light of their high influence on the results.

Most of the studies only examine energy-related indicators and GWP, but in order to avoid impact transfers a more exhaustive

impact assessment methodology should be used. When this type of methodology is used, the most up-to-date one should be chosen and if normalization is performed, the result should also be provided without this step accordingly to LCA international standard such as the ISO standards14040 and 14044 [4,5] and the ILCD handbook [48].

Further LCA on PVs should be made because their environmental impacts are expected to decrease: due to further improvements such as higher cell efficiency, reduction in energy consumption during the modules production, panels recycling, etc. Moreover, the impact of the intermittency of electricity production by PVs should be included in future studies in order to compare with other electricity sources. New PV types such as organic panels should also be examined.

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